Double limit pricing

van der Meijden, Gerard; Ryszka, Karolina; Withagen, Cees

published in
Journal of Environmental Economics and Management
2018

DOI (link to publisher)
10.1016/j.jeem.2018.03.010

document version
Publisher's PDF, also known as Version of record

document license
Article 25fa Dutch Copyright Act

Journal of Environmental Economics and Management 89 (2018) 153–167

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Double limit pricing[☆]

Gerard van der Meijden[a,*], Karolina Ryszka[b], Cees Withagen[c,a]

[a] *Vrije Universiteit Amsterdam, Tinbergen Institute, The Netherlands*
[b] *Ecorys, The Netherlands*
[c] *IPAG Business School, Paris, France*

ARTICLE INFO

Article history:
Received 22 December 2015
Revised 16 March 2018
Accepted 28 March 2018
Available online 30 March 2018

JEL codes:
Q31
Q37

Keywords:
Limit pricing
Non-renewable resource
Monopoly
Climate policy

ABSTRACT

We study oil extraction by a monopolist who faces demand from a climate-aware and a climate-ignorant region. A renewable, perfect substitute for oil is available at constant unit cost. The climate-aware region uses a carbon tax and a renewables subsidy as policy instruments. Due to heterogeneity in climate policies between regions, the oil price path possibly contains two limit-pricing phases. We specify conditions under which a tightening of climate policies results in lower initial carbon emissions. A renewables subsidy and a carbon tax effectively force the monopolist to sell more oil to the climate-ignorant region, during the stage when demand from the climate-aware region has already vanished. We calibrate the model and numerically investigate climate damage and welfare effects of the policies of the climate-aware region. We find that both the carbon tax and a renewables subsidy lower climate damage, even though cumulative emissions are fixed.

1. Introduction

The design of climate policies requires a good understanding of the effects of these policies on markets for fossil fuels, as 78 percent of the increase in greenhouse gas emissions between 1970 and 2010 consisted of carbon emissions from fossil fuel combustion and industrial processes (IPCC, 2014). Most of globally traded fossil fuels, in particular oil, are exported by a small group of countries. OPEC, for example, owns 73 percent of the world's proven reserves (EIA, 2016a). It has been shown theoretically that imperfect competition affects the time profile of the supply of non-renewable resources such as fossil fuels. Typically, monopolistic supply slows down the speed of extraction—"the monopolist is the conservationist's best friend" (cf. Dasgupta and Heal, 1979, p. 329)—and results in a final limit-pricing phase during which the monopolist marginally undercuts the price of substitutes to prevent them from entering the market (cf. Hoel, 1978; Salant, 1979). This paper shows that the move away from the perfectly competitive framework has even more pronounced consequences when climate policies are in place which differ between 'climate-aware' regions, like the European Union, and 'climate-ignorant' regions which have not yet

☆ The authors would like to thank Julien Daubanes, Niko Jaakkola, Rick van der Ploeg, Ingmar Schumacher, Hubert Stahn, two anonymous referees, and participants at the Tinbergen conference (Amsterdam, 2016), the EAERE conference (Zurich, 2016), the SURED conference (Banyuls-sur-Mer, 2016), the FAERE conference (Bordeaux, 2016), the Environmental and Natural Resources Conservation workshop (Montpellier, 2016), the CESifo Area Conference on Energy and Climate Economics (Munich, 2016), the Conference in honour of John Hartwick (October 2017, Kingston, Ontario), and the Workshop in memory of Pierre Lasserre (October 2017, Montréal, Québec) for their valuable comments. The authors gratefully acknowledge financial support from FP7-IDEAS-ERC Grant No. 269788 (GP).

* Corresponding author. Department of Spatial Economics, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV, Amsterdam, The Netherlands.

E-mail address: g.c.vander.meijden@vu.nl (G. van der Meijden).

https://doi.org/10.1016/j.jeem.2018.03.010
0095-0696/

introduced policies to reduce global warming.

We demonstrate that, in such a setting, both the fossil extraction path and the effects of (unilateral) climate policies differ markedly from those under perfect competition. Our framework of a monopolist owning a finite resource stock and exporting fossil fuels to different regions with unilateral climate policies in place enables us to characterize the deviations from the perfectly competitive equilibrium and to investigate the effects of different types of unilateral climate policies on welfare and climate damage.

Most of the existing literature on combating climate change assumes perfectly competitive markets for fossil fuels. This is true for Integrated Assessment Models that aim at characterizing optimal climate policies (cf. Nordhaus, 2013; Golosov et al., 2014), but also for the literature on the effects of suboptimal climate policies, such as Sinn (2008, 2012), who investigates the so-called 'Green Paradox' in a single-region framework, and papers studying unilateral measures to fight global warming in multi-region models (cf. Copeland and Taylor, 2005; Eichner and Pethig, 2011; Hoel, 2011; Fischer and Salant, 2014; Ryszka and Withagen, 2014; Aichele and Felbermayr, 2015). There are only a few studies in the field of climate change economics which move away from perfect competition. Strand (2013) and Karp et al. (2016) employ a game theoretical setting in which a resource-importing bloc and a resource-importing fringe face a group of resource exporters. Strand (2013) compares a carbon tax and a cap-and-trade scheme in order to identify the optimal policy strategies of both players in a static environment, whereas Karp et al. (2016) study a dynamic game where the players use either taxes or quotas to exercise market power in the presence of a group of non-strategic developing countries. Kagan et al. (2015) investigate oil extraction and carbon accumulation for various production function specifications for both open- and closed-loop Nash equilibria, and compare these with the efficient and competitive outcomes. Their model is based on Liski and Tahvonen (2004) who characterize Markov perfect strategies for coalitions of resource-importing and exporting countries.

These papers, however, do not account for the existence of a backstop technology, and, therefore, are not able to study limit-pricing strategies that fossil suppliers might pursue to prevent producers of renewable energy from entering the market. The seminal early literature investigating behaviour by monopolistic non-renewable resource suppliers (cf. Hoel, 1978; Gilbert and Goldman, 1978; Salant, 1979; Stiglitz and Dasgupta, 1981, 1982; Hoel, 1983) does not pay attention to climate policies. Hassler et al. (2010) study monopolistic fossil supply in the presence of a backstop technology and climate damage caused by carbon emissions. However, they assume that the backstop technology makes oil 'superfluous' once it arrives, implying that limit pricing does not occur. Literature on the effects of climate policy in a limit pricing framework is scarce. Jaakkola (2015) studies equilibrium climate policies in a differential game between a resource monopolist and a producer of a backstop which becomes cheaper over time due to investments, giving rise to a regime of limit-pricing behaviour with a declining price over time. In a recent paper, Andrade de Sá and Daubanes (2016) argue that demand for oil is inelastic, implying that the monopolist will choose for limit pricing throughout. As a result, carbon taxes are ineffective and backstop subsidies increase resource extraction. Our analysis shows that, also in the case of elastic resource demand, limit pricing may be more important than suggested by conventional analyses of climate policy effects.

In this paper, we focus on the global oil market, which is responsible for 38 percent of carbon emissions from primary energy supply (IEA, 2016). We consider a monopolist that owns a finite stock of oil and faces constant unit extraction costs and the presence of a renewable perfect substitute with constant marginal production costs. Resource demand comes from a climate-aware region, which employs both a carbon tax and a renewables subsidy, and from a climate-ignorant region, which does not have any climate policies in place. The equilibrium on the oil market depends on whether there are arbitrators on the market, who can cheaply store oil. When arbitrators, who can store oil without costs, are present, the monopolist is constrained to set a price that is continuous over time. However, if storage costs are prohibitively high, arbitrage is not possible and the monopolist is free to choose a discontinuous price path.

The situation in reality lies somewhere in between these two extremes. Many nations have built strategic oil reserves and private actors have created stockpiles. Nevertheless, it is difficult to find reliable estimates of global oil inventories, as some countries, such as Russia and China, do not report their inventory levels and figures for many other countries, such as Angola, Nigeria or Brazil, are not trustworthy.[1] Furthermore, much oil is stashed in tankers, waiting off-coast for higher prices. Global crude inventories are estimated to be around 17 billion barrels in non-OECD countries and around 12 billion barrels in OECD countries (Strumpf and Friedman, 2016). With a world liquid fuel consumption at around 96.26 million barrels per day, this means that there is enough crude oil to satisfy global consumption for 176 days (EIA, 2016b). The inventory of the US's 'Strategic Petroleum Reserves' (SPR) amounted to 695.1 million barrels in September 2016, corresponding to around 36 days of oil at the average US daily consumption level of 19.4 million barrels in 2015 (SPR, 2016; EIA, 2016c).

Whereas the purpose of the strategic petroleum reserves in the US and other countries is to stabilize supplies, there are calls for supply releases to moderate price increases (Regnier, 2007). Although global oil prices dropped after President Trump announced his plan to finance his tax plans by selling half of the US's strategic reserve in May 2017, there is disagreement in the literature on whether the use of the reserves is an effective tool to stabilize the oil markets and whether the existing inventory is sufficient to play this stabilizing role.[2] Yet, these stockpiles might facilitate speculation: Kesicki (2010) notes that "the only way

[1] See 'The Wall Street Journal', July 2016: http://www.wsj.com/articles/how-much-oil-is-in-storage-globally-take-a-guess-1469380040.

[2] For a short discussion see Demirer and Kutan (2010). In their paper, they examine the informational efficiency of crude oil spot and futures markets with respect to SPR announcements. Their results suggest that the SPR program is effective in stabilizing the oil market. Following the announcements, the market adjusts prices upward (downward) after notification of inventory release (purchase of more inventories), lasting about a week following the announcement date. Yet, there are no statistically significant cumulative abnormal returns.

speculation can persistently influence the oil price is due to accumulation of the physical commodity." He conducts a historical analysis which reveals that price surges are accompanied by an accumulation of crude oil in inventories. Kaufmann (2011) attributes a role to speculation in the oil price spike and collapse of 2007–2008 on the grounds of, amongst others, a significant increase in private US crude oil inventories since 2004.

In the current paper, we restrict attention to the case with perfect arbitrage, implying that the equilibrium price does not exhibit discontinuities. In an accompanying paper (Van der Meijden et al., 2017), we analyze the equilibrium without arbitrage possibilities.[3]

Our main findings are as follows. First, we find that the equilibrium path may contain two limit-pricing phases: a 'familiar' one just before the depletion of oil reserves, and a 'surprising' one just before the demand from the climate-aware region vanishes due to climate policies. The reason is that the monopolist may want to postpone the moment of losing demand from the climate aware region by introducing an intermediate limit-pricing regime. Accordingly, in a world with heterogeneous climate policies, it becomes even more important to take the effects of limit pricing into account. Second, a tightening of climate policies does not necessarily result in a so-called 'Weak Green Paradox': we provide conditions under which initial carbon emissions go down. Third, in our calibrated model, a renewables subsidy and a carbon tax both decrease the share of the oil reserves sold to the climate-aware region and increase the share of the oil reserves supplied during the stage in which demand from the climate-aware region has vanished. Fourth, our calibrated model shows that, although a renewables subsidy increases climate damages under perfect competition, this outcome is reversed in the monopolistic equilibrium with arbitrators on the market: a renewables subsidy lowers climate damage, even though cumulative oil supply remains unchanged.

The remainder of the paper is structured as follows. Section 2 describes the model and derives the market equilibrium. Section 3 calibrates the model and performs a policy and welfare analysis. Section 4 concludes and discusses our results.

2. The model

2.1. The monopolist's problem

Energy demand originates from two regions, A and B. Energy supply comes from oil and renewables. Renewable energy is competitively produced in both regions at a unit cost of $b > 0$, whereas oil is supplied by a monopolist in a third region facing unit extraction cost $k \geq 0$. Hence, we neglect set-up costs for renewables and stock-dependent extraction cost for non-renewables (cf. Heal, 1976). We assume that the two types of energy are perfect substitutes.[4] Region A conducts an active climate change policy by imposing a unit carbon tax τ on its consumers and by giving a subsidy σ on the use of renewables. We assume τ and σ to be constant over time.[5] Let us define aggregate demand for oil as $q \equiv q_A + q_B$, consisting of demand q_A from region A and demand q_B from region B. We split up the monopolist's problem in two stages. Stage 1 starts at time zero and lasts until time T_2. During stage 1, the producer price, p, does not exceed $\widehat{b}$, defined as $\widehat{b} \equiv b - \sigma - \tau$. Hence, during stage 1, region A's consumer price of renewables, $b - \sigma$, is not smaller than region A's consumer price of oil, $p + \tau$. Moreover, given that the tax and the subsidy are both non-negative, the consumer price of oil in region B, p, is smaller than the price of renewables in this region, b. Hence, in region B there is only demand for oil. It will be shown that the first stage typically has two phases.[6] In the first phase, from time zero till T_1, the producer price is strictly below $\widehat{b}$ and both regions use only oil. In the second phase of the first stage, the producer price is equal to $\widehat{b}$. This is a phase with limit pricing in region A. Region A's demand for oil in this phase is denoted by $\widehat{q}_A$, region B's demand by $\widehat{q}_B$, and aggregate demand by $\widehat{q} = \widehat{q}_A + \widehat{q}_B$. At the limit price, renewables do not compete with oil in region B. But in region A, consumers are indifferent between oil and renewables. Given the linear cost structure of extraction of oil, the monopolist would like to serve the entire market in region A. This can be achieved by assuming that the monopolist acts as a Stackelberg leader. Alternatively, we assume that the monopolist will marginally undercut the limit price, as a means to keep renewables off the market.[7] Stage 2 starts at time T_2 and lasts until time T_4. In this stage, the price is strictly above $\widehat{b}$, so that region A only uses renewables, but region B still relies solely on oil as long as the producer price is below b. In the first phase of this stage, from time T_2 until time $T_3 \leq T_4$ the consumer price is strictly below b and region B relies on oil only. In the second phase the price equals b and, as in the case of limit pricing in region A, region B still uses only oil, until the entire oil stock is exhausted, due to our assumption that $k < b$.

The optimality of this sequence of regimes is derived below and the underlying intuition is given as well. We denote the producer price in the first stage, when $t < T_2$, by $p_1(q)$, and the producer price when $t \geq T_2$, by $p_2(q)$. As explained above we need $p_1(q) \leq \widehat{b}$ in the first stage. In the second stage, the fossil price in region B should not exceed the renewables price in region B: $p_2(q) \leq b$, and the consumer price of fossil in region A, $p_2(q) + \tau$, should be prohibitively high for the consumers in that region

[3] Hoel (1984) studies the case without arbitrage in a model in which oil is used for several purposes and there exists perfect substitutes for some, but not for all of its uses.

[4] It has been shown by Van der Meijden and Withagen (2017) that the equilibrium with imperfect substitution converges tot the equilibrium with perfect substitution for high values of the elasticity of substitution, in a model in which demand is exerted by a single region.

[5] Constancy of the carbon tax can be motivated by constant marginal damages from carbon emissions, proportional to the use of oil (cf. Hoel, 2011). Constancy of the renewables subsidy is convenient for the exposition of the results.

[6] Throughout, we refer to the time intervals $[0, T_2]$ and $[T_2, T_4]$ as stages and to subintervals within the stages, e.g., $[T_1, T_2]$ as phases.

[7] Note that with convex extraction costs, the monopolist may not want to serve the entire market at the limit price (cf. Salant, 1976).

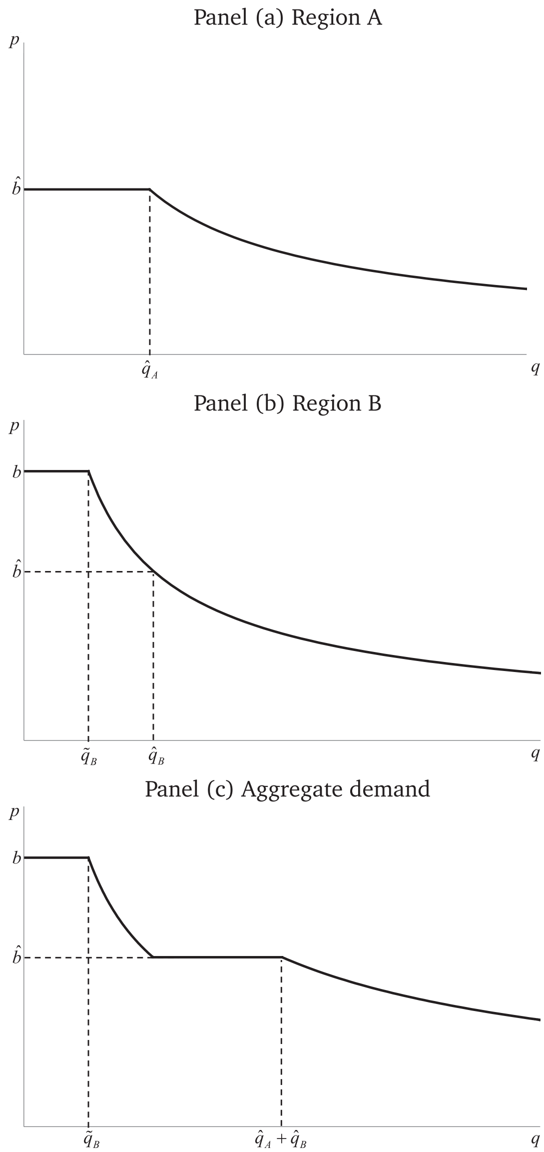


Fig. 1. Regional and aggregate demand.

not to demand oil: $p_2(q) + \tau > b - \sigma$. Demand is illustrated in Fig. 1. The variables $\widetilde{q}_A$ and $\widetilde{q}_B$ represent demand in regions A and B if the consumer price is b.

The switching time, T_2, the final time of oil use, T_4, and the remaining resource stock at the switching time, S_{T_2}, are optimally chosen by the monopolist for given subsidy and tax rates. We tackle the maximization problem of the monopolist by using two-stage optimal control theory (cf. Tomiyama, 1985; Makris, 2001; Valente, 2010). The idea is to first solve the problems in the two stages separately for given T_2, T_4, and S_{T_2}.

The stage 1 problem reads

$$\Lambda_1(T_2, S_0, S_{T_2}) = \max_q \int_0^{T_2} e^{-rt} \left(p_1(q(t)) - k\right) q(t)dt, \tag{1a}$$

subject to

$$\dot{S}(t) = -q(t), \quad q(t) \geq 0, \; S(t) \geq 0, \quad S(0) = S_0, S(T_2) = S_{T_2}, \tag{1b}$$

$$\widehat{b} \geq p_1(q(t)). \tag{1c}$$

The stage 2 problem reads

$$\Lambda_2(T_2, T_4, S_{T_2}) = \max_q \int_{T_2}^{T_4} e^{-rt} \left(p_2(q(t)) - k\right) q(t)dt, \tag{2a}$$

subject to

$$\dot{S}(t) = -q(t), \quad q(t) \geq 0, \; S(t) \geq 0, \quad S(T_2) = S_{T_2}, \tag{2b}$$

$$b \geq p_2(q(t)), \tag{2c}$$

$$p_2(q(t)) \geq \hat{b}. \tag{2d}$$

Subsequently, we determine the optimal T_2, T_4 and S_{T_2} by solving

$$\Lambda(S_0) = \max_{T_2, T_4, S_{T_2}} \Lambda_1(T_2, S_0, S_{T_2}) + \Lambda_2(T_2, T_4, S_{T_2}). \tag{3}$$

To ensure that the second-order conditions are satisfied, we assume the net revenue, $(p_1(q) - k)q$, to be strictly concave in q for $p_1(q) < \hat{b}$, and $(p_2(q) - k)q$ to be strictly concave in q for $\hat{b} < p_2(q) < b$.

Consider the problem in the first stage. The Hamiltonian and the Lagrangian (neglecting the non-negativity constraint on the extraction rate) read

$$\mathcal{H}_1(q, \lambda_1, t) = e^{-rt}(p_1(q) - k)q - \lambda_1 q, \tag{4}$$

$$\mathcal{L}_1(q, \lambda_1, t) = e^{-rt}(p_1(q) - k)q - \lambda_1 q + \mu_{11}(\hat{b} - p_1(q)). \tag{5}$$

In the absence of stock-dependent extraction costs, it follows from the Hotelling rule that the shadow price of the resource stock, λ_1, is constant. The non-negative multiplier μ_{11} corresponds with (1c). The Lagrangian is maximized with respect to the extraction rate. Hence, for $q > 0$, we have

$$e^{-rt}(p_1'(q)q + p_1(q) - k) = \lambda_1 - \mu_{11}p_1'(q). \tag{6}$$

This equation says that if the restriction $\hat{b} \geq p_1(q)$ is not binding (so that $\mu_{11} = 0$), the present value of net marginal revenues of extraction (left hand side) equals the shadow cost λ_1 of the resource. If limit pricing occurs, the monopolist would want to decrease supply and thereby increase the price. The marginal cost of not being able to do this is $-\mu_{11}p_1'(\hat{q}_A)$.

The Hamiltonian and Lagrangian of the second stage read, respectively,

$$\mathcal{H}_2(q, \lambda_2, t) = e^{-rt}(p_2(q) - k)q - \lambda_2 q, \tag{7a}$$

$$\mathcal{L}_2(q, \lambda_2, t) = e^{-rt}(p_2(q) - k)q - \lambda_2 q + \mu_{21}(b - p_2(q)) + \mu_{22}(p_2(q) - \hat{b}), \tag{7b}$$

where μ_{21} and μ_{22} are the non-negative Lagrange multipliers associated with the inequalities (2c) and (2d), respectively. In the second stage, the necessary condition with respect to extraction reads

$$e^{-rt}(p_2'(q)q + p_2(q) - k) = \lambda_2 + \mu_{21}p_2'(q) - \mu_{22}p_2'(q). \tag{8}$$

In order to understand the three additional necessary conditions involving T_2, T_4 and S_{T_2}, note that from optimal control theory (cf. Theorem 3.9 in Seierstad and Sydsæter, 1987, p. 213), we know

$$\mathcal{H}_1(T_2) = \frac{\partial \Lambda_1(T_2, S_0, S_{T_2})}{\partial T_2}, \tag{9a}$$

$$\mathcal{H}_2(T_2) = -\frac{\partial \Lambda_2(T_2, S_0, S_{T_2})}{\partial T_2}, \tag{9b}$$

$$\mathcal{H}_2(T_4) = \frac{\Lambda_2(T_2, T_4, S_{T_2})}{\partial T_4}. \tag{9c}$$

Equation (9c) implies that the monopolist chooses the final time T_4 such that

$$\mathcal{H}_2(T_4) = 0. \tag{10}$$

If the monopolist would be free to choose any $T_2 \in (0, T_4)$ and $S_{T_2} \in (0, S_0)$, it would make sure that the following matching conditions hold (cf. Tomiyama, 1985; Makris, 2001; Valente, 2010)[8]:

$$\lambda_1 = \lambda_2, \tag{11a}$$

[8] By $\mathcal{H}_1(T_2^-)$ we denote the limit of the value of the Hamiltonian in the first stage for time approaching T_2 from below, and by $\mathcal{H}_2(T_2^+)$ the value of the Hamiltonian in the second stage for time approaching T_2 from above.

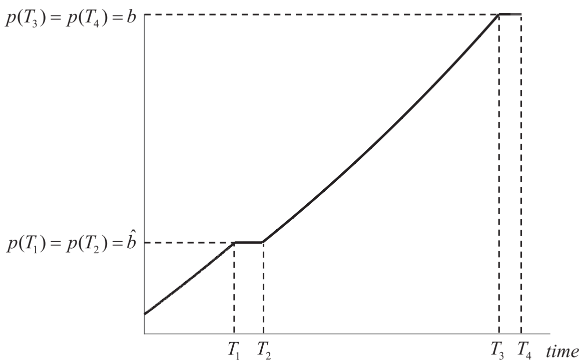


Fig. 2. Equilibrium price path.

$$\mathcal{H}_1(T_2^-) = \mathcal{H}_2(T_2^+). \tag{11b}$$

Intuitively, condition (11a) ensures that the monopolist cannot gain by reallocating cumulative extraction between the two stages, because the shadow price of the stock is the same in both stages. Similarly, if (11b) holds, it is clear from (9a)-(9b) that the monopolist cannot increase profits by reallocating time between the two stages. Van der Meijden et al. (2017) show that a solution satisfying the matching conditions (11a)-(11b) implies an upward jump in the price at the switching time. However, with arbitrators on the market, such an expected jump in the price must be ruled out: The price path must be continuous. Price continuity implies that the monopolist faces restrictions on the T_2 and S_{T_2} it can choose. As a result, when taking the existence of arbitrators into account, the standard matching conditions from two-stage optimal control theory (11a)-(11b) have to be replaced by alternative conditions that will be discussed in the description of the equilibrium in the next subsection.

2.2. Equilibrium

A typical equilibrium price path is depicted in Fig. 2. Proposition A. 1 in Online Appendix A.2 provides a formal characterization. In this section, we take an intuitive approach and argue that all possible equilibria are special cases of the one shown in Fig. 2. Furthermore, to avoid cluttering the discussion, we restrict attention to the case in which marginal profits during stage 1 and stage 2, defined as $\pi_1(q(t)) \equiv p_1(q(t)) - k + p_1'(q(t))q(t)$ for $0 \le t \le T_2$ and $\pi_2(q(t)) \equiv p_2(q(t)) - k + p_2'(q(t))q(t)$ for $T_2 \le t \le T_4$, respectively, are strictly positive throughout. This is ensured by imposing $\pi_1(\widehat{q}) > 0$ and $\pi_2(\widehat{q}_B) > 0$, due to strict concavity of net revenues. Online Appendix A.2 discusses the cases with non-positive marginal profits.[9]

We find that for an initial resource stock small enough, it is optimal to have limit pricing at price b from the start. This occurs for the initial stock S_0 smaller than or equal to a critical level, denoted by S_{01}. For a larger initial stock, there is scope for an initial phase with the producer price below b. If the stock is not too large, not larger than another critical level $S_{02}(> S_{01})$, the monopolist will serve only the market in the region without climate policy. The critical level S_{02} is determined as the initial stock for which the monopolist will charge an initial price exactly equal to $\widehat{b}$ and, if the initial resource stock is smaller than or equal to S_{02}, the monopolist just acts as if there were only region B. With a still larger initial stock, the initial price charged in this single market would be smaller than $\widehat{b}$, so that also demand from region A would be attracted. Then region A enters the picture. For initial stocks not too large, smaller than some S_{03}, there may be limit pricing for a while at price $\widehat{b}$. For larger initial stocks, the initial price will even be below $\widehat{b}$, which is the case shown in Fig. 2.

Let us now consider the case in which the initial stock is indeed large enough to obtain $p(0) < \widehat{b}$ (i.e., $S_0 > S_{03}$), implying $T_1 > 0$. Working backwards in time, we will discuss which of the four phases in Fig. 2 necessarily exist and which of them may be degenerate.

First, the final limit-pricing phase during T_3 and T_4 is always there. Intuitively, the monopolist could sell its last unit of fossil fuel at $T_3 \le T_4$ against the price $p = b$ yielding marginal profit

$$e^{-rT_3}(p'(\widetilde{q}_B)\widetilde{q}_B + b - k). \tag{12a}$$

Alternatively, the last unit of fossil could be conserved and sold right after exhaustion of the rest of the stock, i.e., at $T_4^+ \equiv \lim_{t \downarrow T_4} t$ against price $p = b$. As $q(T_4^+) = 0$, marginal profit would then boil down to average profit and equal

[9] Proposition A. 2 in Online Appendix A.2 shows that, irrespective of the initial stock S_0, if $\pi_2(\widetilde{q}_B) \le 0$, we obtain $T_1 = T_2 = T_3 = 0$; if $\pi_2(\widehat{q}_B) \le 0$ we obtain $T_1 = T_2 = 0$; and if $\pi_1(\widehat{q}) \le 0$ we obtain $T_1 = 0$. Negative marginal profits will occur, for instance, if oil demand is inelastic (as assumed by, e.g., Andrade de Sá and Daubanes, 2016).

$$e^{-rT_4}(b-k). \tag{12b}$$

Equalizing marginal profits of both options requires $T_4 > T_3$, implying that there is always a final interval of time with limit pricing.

Second, the phase from T_2 until T_3, with the producer price increasing over time from $\hat{b}$ to b, necessarily exists as well, because of price continuity.

Third, the limit-pricing phase between T_1 and T_2, may, however, be degenerate. To understand the occurrence or absence of intermediate limit pricing, note first that, from T_2 onward, the monopolist essentially solves a standard ('one-stage') optimal control problem. Price continuity requires that $p(T_2) = \hat{b}$, which gives a unique stock, $S_{T_2} = S_{02}$ (a smaller (larger) stock would yield a price at $t = T_2$ larger (smaller) than $\hat{b}$). Hence, the monopolist is not free to choose cumulative extraction during the two stages. As a result, the matching conditions (11a)-(11b) do not apply as necessary conditions and should be replaced by:

$$p_1(q(T_2^-)) = p_2(q(T_2^+)) = \hat{b}, \tag{11a$'$}$$

$$\mathcal{H}_1(T_2^-) \leq \mathcal{H}_2(T_2^+) \text{ and } \left(\mathcal{H}_1(T_2^-) - \mathcal{H}_2(T_2^+)\right)(T_2 - T_1) = 0. \tag{11b$'$}$$

Condition (11a′) just requires continuity of the price. The first part of condition (11b′) requires that T_2 is chosen optimally (see (9a) and (9b)). The second part says that if the maximization problem yields a strict inequality, the intermediate limit pricing phase vanishes. Intuitively, if, without an intermediate limit-pricing phase, $\mathcal{H}_1(T_2^-)$ would be larger than $\mathcal{H}_2(T_2^+)$, the monopolist could increase profits by increasing T_2, the duration of the first stage (when it is supplying to both markets). Increasing T_2 without changing S_{T_2} is possible by introducing a limit pricing regime with a duration such that $\mathcal{H}_1(T_2^-) = \mathcal{H}_2(T_2^+)$ holds. Conversely, if we would have $\mathcal{H}_1(T_2^-) < \mathcal{H}_2(T_2^+)$ without an intermediate limit-pricing phase, the monopolist would like to decrease the duration of the first stage in order to increase profits. However, decreasing T_2 without changing S_{T_2} would require a downward shift in the price path until T_2, which would imply $p(T_2^-) < \hat{b}$, which is prohibited by price continuity. Hence, the Hamiltonian must be continuous at $t = T_2$ if and only if there exists an intermediate limit-pricing phase from T_1 until T_2. The interpretation is that if profits per period drop significantly when demand from region A vanishes, the monopolist postpones this switching moment by introducing an intermediate limit-pricing phase.

Finally, the initial phase from 0 until T_1 in Fig. 2 exists, because the maximum duration of the intermediate limit pricing regime is finite.[10] Hence, if the initial stock is large enough (i.e., $S_0 > S_{03}$), there will be an initial phase during which $p < \hat{b}$.

3. Policy and welfare

In this section, we discuss how oil supply, climate damage and welfare are affected by the introduction or tightening of climate change policies in one region, whereas the other region stays inactive. We first investigate what happens with initial fossil supply, $q(0)$, proceed by analyzing the effects on the entire time path $q(t)$, and finally discuss the consequences for climate damage and welfare.

3.1. Initial extraction

It was shown in the previous section that, for a resource stock large enough for the monopolist to start supplying to both markets, there are three possibilities for the first stage. One possibility is to have limit pricing from the start until the monopolist leaves the market of country A (i.e., $T_2 > T_1 = 0$).

Another possibility is the absence of initial limit pricing—the price hence rises initially, before limit pricing sets in at the end of the first stage (i.e., $0 < T_1 < T_2$). Finally, there is no limit pricing in the first stage at all (i.e., $0 < T_1 = T_2$). In the first two cases, the effect of a carbon tax and a renewables subsidy on initial extraction can be determined analytically, as shown in Proposition 1.[11]

Proposition 1. *Suppose the initial resource stock is large enough for the monopolist to start supplying to both markets (i.e., $S_0 > S_{02}$) and that there is an intermediate limit-pricing phase (i.e., $T_2 > T_1$).*

(i) *If the monopolist starts with limit pricing (which occurs if $S_{02} < S_0 \leq S_{03}$), an increase in the renewables subsidy increases initial extraction. An increase in the carbon tax leaves initial extraction unaffected.*
(ii) *If the monopolist does not start with limit pricing (which occurs if $S_0 > S_{03}$), an increase in the renewables subsidy or an increase in the carbon tax lowers initial resource extraction.*

[10] Online Appendix A.2 shows that the maximum duration of intermediate limit pricing is given by $\ln(p_2'(\hat{q}_B)\hat{q}_B^2 + (\hat{b}-k)\hat{q}/[p_1'(\hat{q})\hat{q}^2 + (\hat{b}-k)\hat{q}])/r$.

[11] The case without intermediate limit pricing is more complex, because then $\mathcal{H}_1(T_2^-) \neq \mathcal{H}_2(T_2^+)$. Although a carbon tax lowers initial extraction, by constructing numerical examples, we have shown that the effect of a renewables subsidy on initial extraction can go either way in this case. Details are available from the authors upon request.

Proof. Part (i). Recall that $p+\tau=\hat{b}=b-\sigma$. Hence, the consumer price of the resource is fixed by the consumer price of renewable energy. Therefore, initial extraction goes up upon an increase in the renewables subsidy (which lowers the consumer price of renewables), but remains unaffected by an increase in the carbon tax (which does not affect the consumer price of renewables). Part (ii). An increase in σ or τ makes the constraints faced by the monopolist more stringent. Hence $d\Lambda(S_0,b,\sigma,\tau)/d\sigma<0$ and $d\Lambda(S_0,b,\sigma,\tau)/d\tau<0$. It is shown in Online Appendix A.3 that $\Lambda(S_0,b,\sigma,\tau)=\mathcal{H}_1(0)/r$, yielding $d\mathcal{H}_1(0)/d\sigma<0$ and $d\mathcal{H}_1(0)/d\tau<0$. Moreover, from the strict concavity of $(p_1(q)-k)q$ in q, $\mathcal{H}_1(0)=-p_1'(q(0))q^2(0)$ implies $d\mathcal{H}_1(0)/dq(0)>0$. Therefore, we get $dq(0)/d\sigma<0$ and $dq(0)/d\tau<0$. □

The implication is that a Weak Green Paradox, i.e., a rise in initial carbon emissions, occurs upon the introduction or increase of a renewables subsidy, if there is limit pricing from the beginning. However, if the initial consumer price of oil is lower than the consumer price of renewables and an intermediate limit-pricing phase exists, the introduction or increase of a subsidy for renewables does not lead to a Weak Green Paradox, but to a decline in initial emissions instead.[12] In the next section, we calibrate our model in order to determine the policy effects on the entire extraction path.

3.2. Calibration

We use the following HARA utility function:

$$U^i\left(\frac{q_i+x_i}{n_i}\right)=\frac{1-\varphi}{\varphi}\left[\left(\frac{\psi\left(\frac{q_i+x_i}{n_i}\right)}{1-\varphi}+\chi\right)^{\varphi}-\chi^{\varphi}\right],\quad i=A,B, \tag{14}$$

where x_i denotes consumption of renewables and n_i the population size in region i, which we use as a pivotal parameter. Accordingly, demand for oil in region A and B is given by, respectively

$$q_A=\begin{cases} n_A\dfrac{1-\varphi}{\psi}\left[\left(\dfrac{p+\tau}{\psi}\right)^{\frac{1}{\varphi-1}}-\chi\right] & \text{if } p\le\hat{b} \\ 0 & \text{if } p>\hat{b}\end{cases}, \tag{15a}$$

$$q_B=\begin{cases} n_B\dfrac{1-\varphi}{\psi}\left[\left(\dfrac{p}{\psi}\right)^{\frac{1}{\varphi-1}}-\chi\right] & \text{if } p\le b \\ 0 & \text{if } p>b\end{cases}. \tag{15b}$$

Furthermore, in accordance with Hoel (2011), Van der Ploeg (2016), and Benchekroun et al. (2017), we impose climate damages that are linear in the stock of atmospheric carbon. The discounted value of climate damages is given by:

$$Z(t)=\int_t^{\infty}\delta E(s)e^{-r(s-t)}ds, \tag{16}$$

with $\delta>0$ denoting the instantaneous marginal climate damage from oil use and E is the atmospheric stock of carbon, which evolves according to $\dot{E}(t)=\omega q(t)$, where ω represents the carbon content per unit of oil. Hence, the social cost of carbon (SCC), i.e., the present value of current and future damages from a unit of carbon emitted at time t, equals

$$SCC(t)=\frac{1}{\omega}\int_t^{\infty}\delta e^{-r(s-t)}ds=\frac{\delta}{r\omega}. \tag{17}$$

Following Benchekroun et al. (2017), we use data on OPEC's proven oil reserves, global oil consumption, the oil price, extraction costs, and the carbon emission factor for crude oil to calibrate our model.[13] OPEC's proven reserves amount to 1212 billion barrels (EIA, 2017). For OPEC's marginal extraction cost, we take the Middle East and North African oil (MENA) estimate of 18 US$ per barrel from Fischer and Salant (2017). We use a quadratic HARA utility function ($\varphi=2$), yielding linear demand. We choose values for the HARA parameters ψ and χ and the renewables price b to obtain an initial oil demand of 34 billion barrels, an initial oil price of 76 dollars per barrel (in line with the average global crude oil consumption and the crude oil price over the period 2007–2017 (EIA, 2017)), and a price elasticity of oil demand equal to 2.[14] The implied price of renewables, 90 US$/boe,

[12] This result is known in the context of a single oil importer (cf. Van der Meijden and Withagen, 2017), but generalizes to our case with multiple importing countries with heterogeneous climate policies as long as there is an intermediate limit-pricing phase in equilibrium.

[13] We use tC to denote 'metric tonnes of carbon', GtC for 'gigatonnes of carbon', bbl for 'barrels of oil' (one barrel contains about 159 L), BOE for 'barrels of oil equivalent', and US$ for current US dollars.

[14] Empirical estimates for the price elasticity of aggregate oil demand are much lower than 2, often below 0.5 (cf. Hamilton, 2009). If there are multiple suppliers, however, the relevant elasticity of an individual supplier is much higher than the elasticity of aggregate demand (e.g., with m symmetric oligopolists, the individual elasticity equals m times the elasticity of aggregate demand). We use a relatively high value for the elasticity of oil demand as a short-cut way of taking into account the existence of other suppliers next to OPEC (cf. Van der Ploeg, 2012).

Table 1
Calibration.

	Description	Value	Unit
Parameters			
φ	HARA parameter	2	–
ψ	HARA parameter	1.06	–
χ	HARA parameter	107.83	–
ω	emission factor	0.11083	tC/bbl
δ	climate damage parameter	0.3103	tC/bbl
b	renewables price	90	US$/BOE
k	marginal extraction cost	18	US$/bbl
n_A	Size region A	0.1	fraction
n_B	Size region B	0.9	fraction
r	interest rate	0.028	perunage
S_0	initial oil stock	1212	billion bbl
Implied values			
$q(0)$	initial oil consumption	34	billion bbl
$p(0)$	initial oil price	76	US$/bbl
$\varepsilon(0)$	initial price elasticity of demand	2	elasticity
$SCC = \delta/r\omega$	social costs of carbon	100	US$/tC

corresponds to the unit costs of biofuels after 10 years in Fischer and Salant (2017).[15] For the social cost of carbon, we take 100 US$/tC (or 27 US$/tCO_2), which is within the range reported in Nordhaus (2017). We base the size of the policy-active and policy-inactive region, region A and B, respectively, on the carbon emission share of these regions in global emissions. According to Boden et al. (2015), the share of the EU-28 countries in global carbon emissions from fossil-fuel burning, cement production and gas flaring was equal to 10 percent. We interpret the EU-28 as the policy active region and impose $n_A = 0.1$ and $n_B = 0.9$. The carbon content of crude oil is set to $\omega = 0.11083$ ton carbon per barrel (EPA, 2015). For the interest rate, we use the average of the US long-term composite rate on government bonds in 2017, which equals 2.8 percent (U.S. Department of the Treasury, 2017).[16] Each time period in the calibration corresponds to a year. Table 1 contains an overview of the benchmark calibration.

3.3. Time paths

The solid curves in Fig. 3 represent the equilibrium time profiles for the extraction rate (panel (a)) and the oil price (panel (b)), when the policy-active region has imposed a renewables subsidy equal to 10 percent of the renewables price and does not use a carbon tax, i.e. $\sigma = 9$ and $\tau = 0$. In the calibrated model, none of the phases discussed in Section 2.2 is degenerate.

The oil price p starts out at a lower level than the consumer price of renewables in the policy-active region, $b - \sigma$. Over time, the oil price increases and reaches the consumer price of renewables after 13 years. Then, OPEC performs a limit pricing strategy for about 4 years, in order not to loose demand from the policy-active region. At the end of this 4 years lasting intermediate limit-pricing phase, the oil price rises above the consumer price of renewables in the policy-active region, implying that global oil demand jumps down by 3 billion barrels. For 17 more years, the monopolist supplies oil to the region without climate policies at a price that is below that of renewable energy, but increases over time as OPEC's oil stock dwindles.

After 34 years, another limit-pricing phase starts, during which the oil price is set equal to the renewables price, in order to prevent renewables producers in the policy-inactive region to enter the market. This final limit-pricing phase lasts for 15 more years, until OPEC's reserves are exhausted in period 49. The dotted curves in both panels show the equilibrium time profiles under perfect competition. Clearly, there will be no limit-pricing behaviour in the competitive equilibrium. Furthermore, the initial oil price will be much lower (50 US$ compared to 76 US$), extraction will be more rapid, and depletion of the oil stock will occur sooner (after 29 instead of 49 years). The policy-active region, however, would switch much later (after 29 instead of 17 years) to renewable energy, due to the lower initial oil price.

In the remainder of this section, we show how the introduction of a climate policy in one region, with the other region remaining inactive, affects oil supply. So, we now suppose that initially regions A and B are identical in policy terms, or $\tau = \sigma = 0$, and that region A introduces renewables subsidy, $\sigma > 0$, or a carbon tax, $\tau > 0$. Because an intermediate limit-pricing regime may appear once climate policies are in place, it is interesting to show how the entire price and extraction paths are affected by the carbon tax and the renewables subsidy. Fig. 4 compares the equilibrium without climate policies (solid black curves) to a regime with a renewables subsidy (dotted curves in panels (a) and (b)) and a carbon tax (dotted curves in panels (c) and (d)) in our calibrated model.

In line with Proposition 1 (ii), panels (a) and (c) of Fig. 4 show that initial extraction goes down upon the introduction of a carbon tax and renewables subsidy. Panels (b) and (d) show the corresponding price paths. Note that a renewables subsidy and

[15] Fischer and Salant (2017) assume that the backstop price initially equals 115 US$/BOE and asymptotically decreases over time to 10 US$/BOE, due to technological change.

[16] Using the values for r and ω, we get $SCC = \frac{\delta}{r\omega}$. Therefore, in the calibrated model we use $\delta = 100 \cdot 0.028 \cdot 0.11083 = 0.3103$ US$/tC.

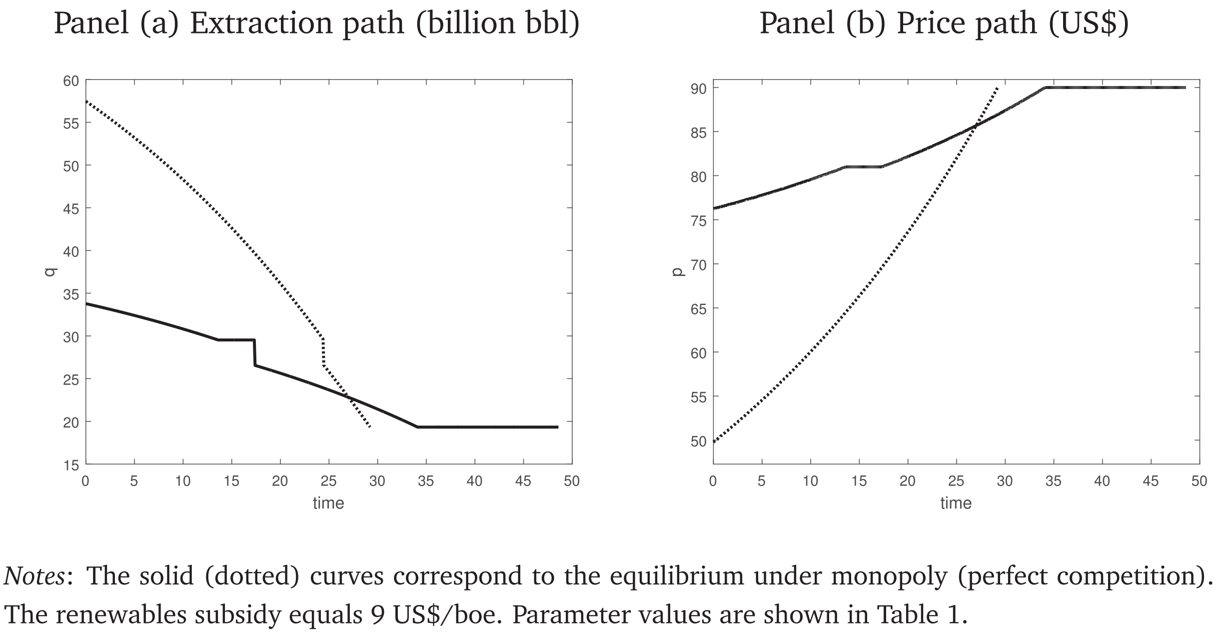


Fig. 3. Equilibrium.

a carbon tax postpone depletion. The reason is that a subsidy and a tax both lower $\hat{b}$ and thus force the monopolist to sell a larger share of its fossil reserves during the second stage, when demand from the climate-aware region has vanished. The duration of the intermediate limit pricing phase in panel (a) is higher than in panel (b). Intuitively, the carbon tax forces the monopolist to sell more during the second stage. Furthermore, the tax lowers the profitability of fossil extraction during the first stage relative to the second stage. The monopolist responds by reducing the duration of the intermediate limit-pricing phase to shorten the first stage. If the tax becomes large enough, the intermediate limit-pricing phase disappears altogether.

3.4. Climate damage and welfare

In this subsection, we examine the consequences of climate policies for climate damage and welfare in our calibrated model and we compare the outcomes under monopoly with those under perfect competition. We assume quasi-linear preferences so that total welfare in region A is defined by

$$W^A = \int_0^\infty e^{-rt}\left(n_A U^A\left(\frac{q_A(t)+x_A(t)}{n_A}\right) - bx_A(t) - p(q_A(t))q_A(t)\right)dt - n_A Z(0), \tag{18}$$

where $E(t) = E_0 + \int_0^t (q_A(s) + q_B(s))ds$ and the climate damage function

$$Z(0) = \int_0^\infty \delta E(s)e^{-rs}ds,$$

from (16). The HARA utility function (14) implies that oil demand is given by (15a). Demand for renewables follows from the condition $dU^A(x_A)/dx_A = b - \sigma$ if $x_A > 0$.

Given the distortions due to monopolistic oil supply and the climate externality, the equilibrium without a carbon tax or a renewables subsidy is clearly second-best. Furthermore, the policy instruments do not only affect efficiency by changing the timing of fossil supply, but also the distribution of welfare between regions A and B and the monopolist by changing the scarcity rent.

Panel (a) of Fig. 5 shows how the share of the oil stock that is sold to the policy-active region depends on region A's climate policies. Panel (b) depicts the share of the stock that is extracted during stage 1 (i.e., when there is still demand for oil from the policy-active region). The solid curves correspond to the monopolistic case (labeled 'M') and the dotted curves to the perfectly competitive equilibrium (labeled 'PC'). The black (grey) curves show the effect of the carbon tax (renewables subsidy). In panel (b) the black and grey curves coincide. The curves show that both the carbon tax and the renewables subsidy cause (intertemporal) carbon leakage: the oil supplier sells a larger share of its reserves to the policy-inactive region (panel (a)) and a larger share during stage 2 (panel (b)), the higher the carbon tax or the renewables subsidy in the policy-active region is. Under monopoly, this effect is relatively stronger and particularly pronounced when moving from a zero tax and subsidy equilibrium

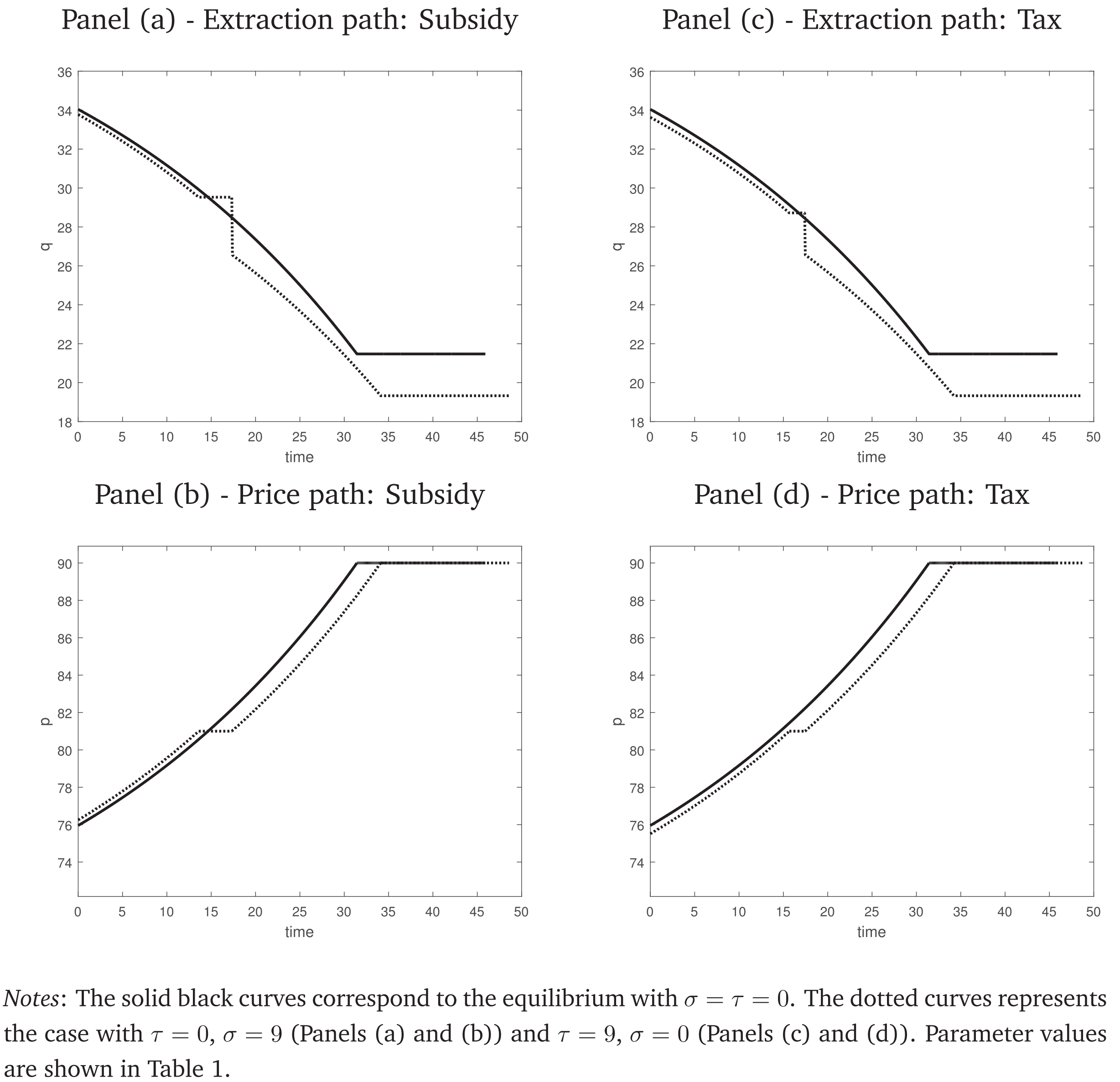


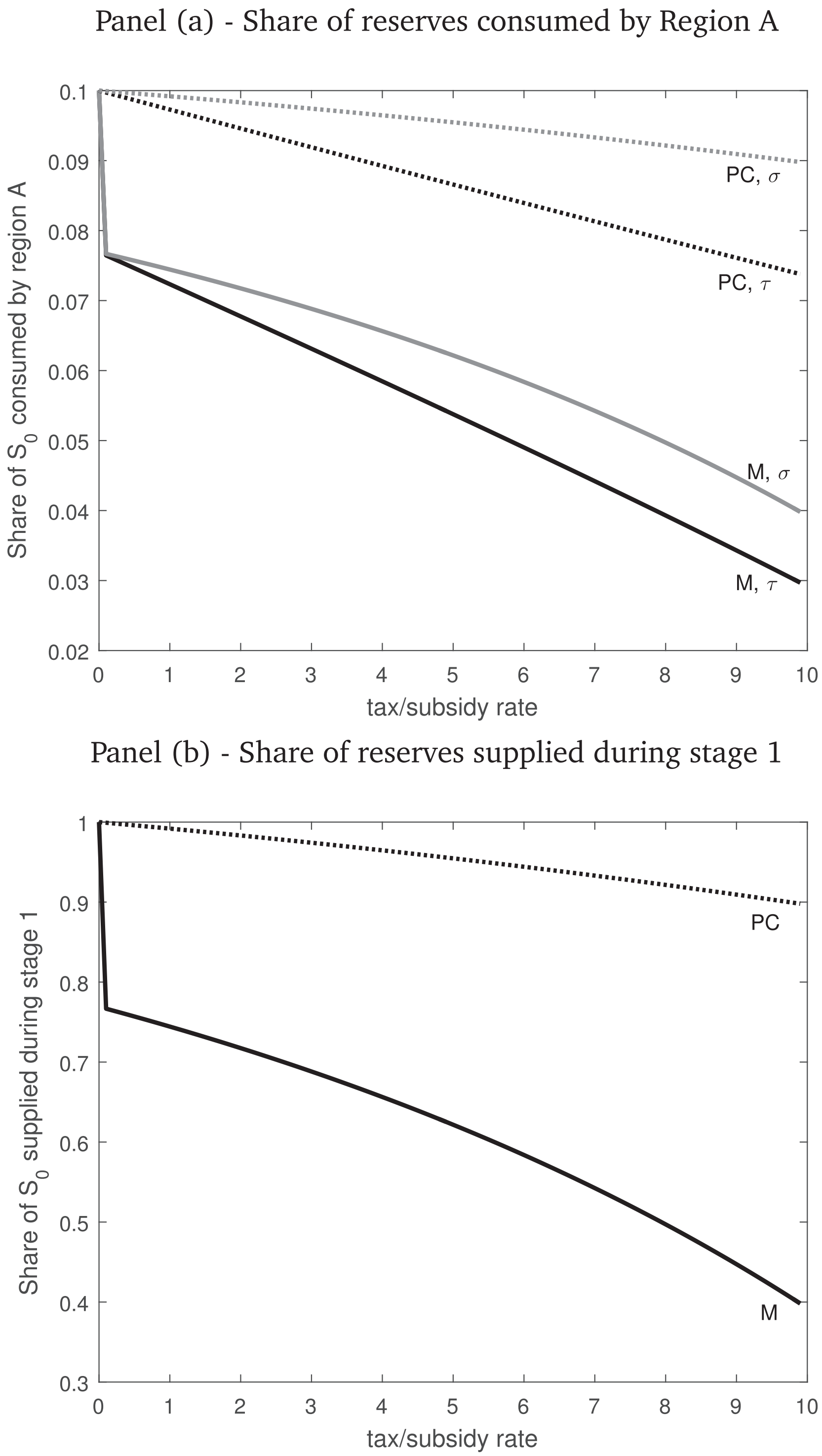
Fig. 4. Effect of climate policies on extraction and price paths.

to an equilibrium with a positive tax or subsidy rate. The reason is that, as a result of the introduction of (even a very small) tax or subsidy, demand from the policy-active region vanishes during the entire final limit-pricing phase.

Fig. 6 shows the effect of a carbon tax and a renewables subsidy on different welfare components for region A: non-green welfare, W_N^A (the integral in (18)), climate damage, Z and total welfare, W^A, which is the difference between the two. The black curves represent the effect of a carbon tax, whereas the grey curves show the effect of a renewables subsidy. Panels (a), (b), and (c) depict the case of monopolistic oil supply. Panels (d), (e), and (f) exhibit the situation under perfectly competitive oil supply.

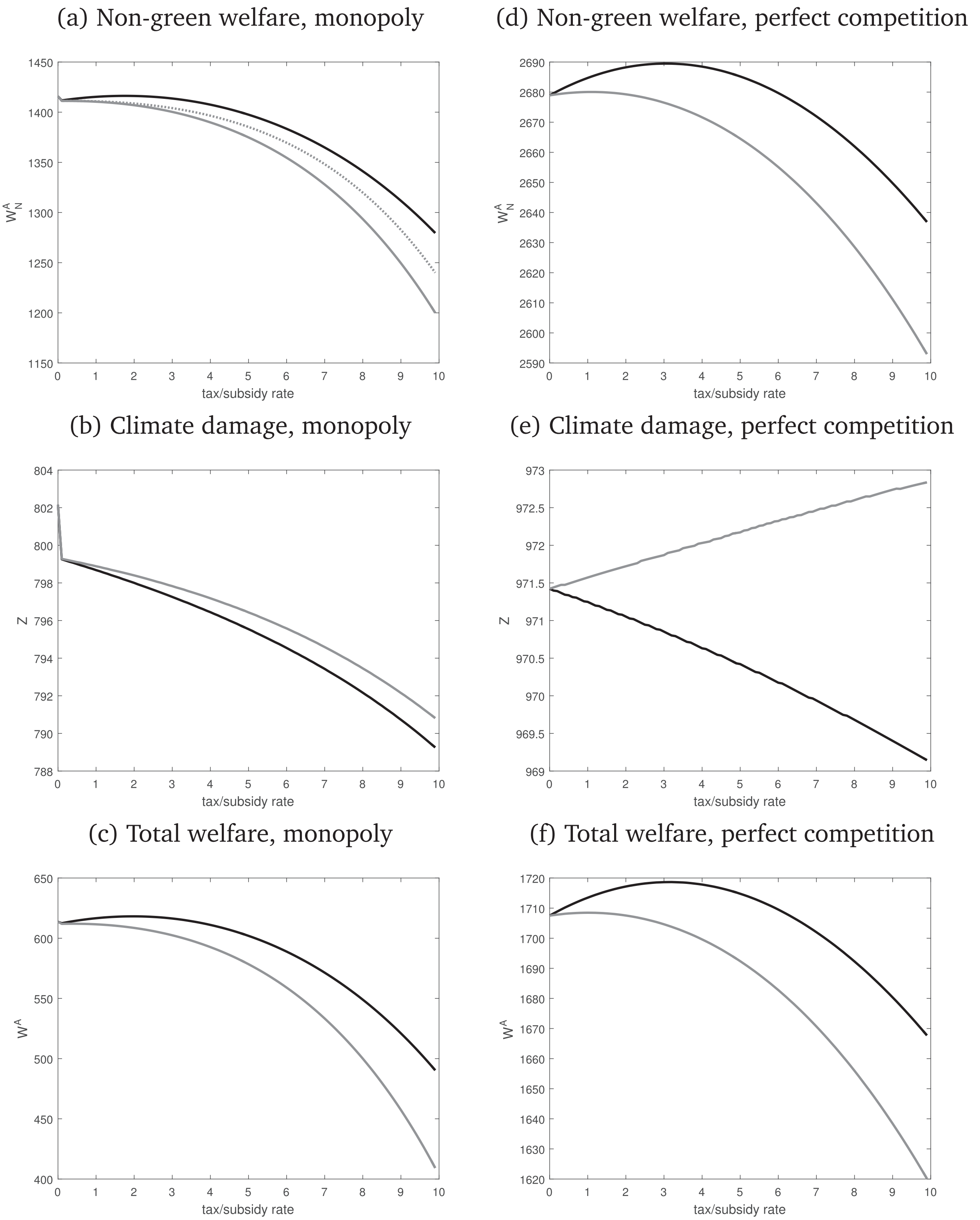
Panel (a) shows that the renewables subsidy lowers non-green welfare, whereas a not too high carbon tax may be beneficial for non-green welfare. The difference between the instruments in terms of welfare effects is partly due to the fact that the renewables subsidy distorts energy use after depletion of the fossil stock, due to the assumption that the subsidy remains in place forever. The dotted curve shows that the effect of a subsidy that is unexpectedly and permanently removed after depletion of the fossil reserve is less harmful for non-green welfare.

It can be seen from panel (b) that the introduction of both a carbon tax and a renewables subsidy lower climate damage. The decrease in damage is especially pronounced when moving from zero to a positive value for one of the two instruments. The reason is that, due to climate policies, demand from the climate aware region vanishes in stage 2. By further increasing the subsidy or the tax, the monopolist is forced to sell a larger share of its reserves in the second stage, which implies that fossil fuel supply is spread out over a longer time horizon, as shown in Fig. 4, which further lowers damage.



Notes: The black curves correspond to the scenarios with a carbon tax. The grey curves correspond to the scenarios with a renewables subsidy. In panel (b), the black and grey curves coincide. The solid (dotted) curves correspond to the equilibrium under monopoly (perfect competition). M denotes monopoly, PC perfect competition. Parameter values are shown in Table 1.

Fig. 5. Intertemporal carbon leakage.



Notes: The black curves correspond to the scenarios with a carbon tax. The grey curves correspond to the scenarios with a renewables subsidy. In panel (a), the dotted grey curve represent the situation of a subsidy that is unexpectedly removed at the moment of depletion of the fossil stock. Parameter values are shown in Table 1.

Fig. 6. Welfare effects of a renewable subsidy and a carbon tax.

Panel (c) shows that the curves for total welfare resemble those for non-green welfare. The reason is that region A only takes into account a small share n_A (10 percent) of global climate damages. Still, the unilaterally second-best carbon tax is close to 2 US$/bbl, which is higher than the marginal climate damage for the policy-active region of 1.11 US$/bbl, but lower than the global marginal climate damage of 11 US$/bbl.

The right column of Fig. 6 exhibits the results of the welfare analysis in case the oil market would be perfectly competitive. Qualitatively, most of the effects of renewables subsidies and carbon taxes are comparable to the monopolistic case. The welfare level, however, differs from the monopolistic case. Non-green welfare is larger under perfect competition (panel (d)). Climate damage, however, is larger as well (panel (e)). In the calibrated model, this implies that aggregate welfare in the policy-active region is higher under perfect competition, as shown in panel (f). The most interesting difference between the monopolistic and perfectly competitive case, however, is that a renewables subsidy lowers climate damage under monopoly and increases climate damage under perfect competition. The reason is that, under monopoly, there is no Weak Green Paradox. Moreover, a renewables subsidy induces the policy-active region to switch much earlier to renewables under monopoly than under perfect competition, as was shown in Fig. 3.

4. Conclusion

This paper offers a full characterization of the equilibrium in a resource extraction framework with monopolistic supply of oil and multiple heterogeneous regions with differential climate policies. Technically, the framework gives rise to a two-stage optimal control problem for the monopolist. It has been shown that with differential climate change policies two stages appear in the equilibrium. In the first stage, both regional markets, i.e., the markets in the regions with and without climate policies, are served (if the initial resource stock is large enough). This initial stage is followed by a second stage in which only the region without climate policies in place is supplied with oil. The latter stage always has a final phase with limit pricing, whereas the former stage may have a limit-pricing phase as well. Because of the presence of arbitrators, the price path is continuous.

Our results are complementary to those of Andrade de Sá and Daubanes (2016). They argue that in case of inelastic demand, oil suppliers choose for limit pricing throughout, which restrains the effectiveness of climate policies such as carbon taxation and renewables subsidies. We show that, also in the case of elastic demand, limit pricing may be more important than suggested by conventional analyses of climate policy effects. The reason is that heterogeneous climate policies may cause an additional, intermediate limit pricing phase. Our numerical welfare analysis suggests that, although a subsidy for renewables increases climate damage under perfect competition due to a Green Paradox effect, under monopoly, the renewables subsidy lowers climate damage. The reason is that the monopolist is forced to sell a larger share of its fossil reserve during the second stage, when demand from the policy active region has vanished. This result is relevant for policy makers.

Another policy relevant issue relates to the social welfare effects in regions that consider to take unilateral action against climate change. Upon the introduction or tightening of climate policies, the monopolist shifts its supply to the unregulated region such that the regulated region switches earlier to renewables. This (intertemporal) carbon leakage effect lowers non-green welfare in the regulated region. We see that in our calibrated model a carbon tax policy may still increase social welfare in this region. A renewables subsidy is less beneficial for or even detrimental to welfare. The conclusion that a carbon tax performs better than a subsidy is maintained even if the subsidy is (unexpectedly) reduced to zero as soon as all oil is depleted. These results are obtained for specific welfare functions, but it is to be expected that at least the superiority of taxation remains valid in more general settings.

Although we have constrained ourselves to studying the case of a pure monopoly, which is not the most accurate representation of the real world, the occurrence of limit-pricing in the model indicates that backstop investments (or subsidies for renewables, as introduced formally in this model) lead to lower initial oil supply if the initial oil stock is large enough. This is the opposite of what is found in case of perfect competition. Hence, in case of large enough oil reserves, we can exclude the occurrence of a Weak Green Paradox as a consequence of climate policy. This concept, however, is not of much use for judging the desirability of climate policies in our framework. The reason is that due to the existence of the limit-pricing phases, the resource extraction and price paths before and after the policy changes may cross several times, implying that a decrease in initial extraction does not necessarily lead to lower climate damages.

Our study exhibits some limitations. We do not derive optimal policies and assume constancy over time of the policy instruments. Moreover, it would be interesting to allow for differences in climate policies between countries within the policy-active world, which would give rise to the existence of additional limit-pricing regimes. Furthermore, we assume that the monopolist is not able to use price discrimination. This is a valid assumption for the oil market, for instance, since oil can be easily shipped and is traded globally. Yet, the assumption might not hold in the case of gas, which is traded mostly regionally or by bilateral trading agreements. Additionally, we do not consider strategic behaviour on the part of the importing and exporting regions. This is an interesting and promising direction to extend the paper. Also, the markets for fossil fuels are not purely monopolistic. Research should be extended so as to include oligopoly or cartel-fringe market structures, which might answer questions related to the sequence of fuel extraction and the conditions under which simultaneous limit-pricing will take place (cf. Benchekroun et al., 2009, 2010, 2017). The model would also gain in value by allowing for technological progress in the backstop technology, for R&D expenditures on developing better backstop technologies, which would allow for decreasing fossil prices and increasing energy use during limit-pricing phases (cf. Jaakkola, 2015) and partial exhaustion if the marginal costs of the backstop technology rapidly fall below the marginal extraction cost of fossil fuels (cf. Fischer and Salant, 2017). Finally, it would be interesting to allow for set-up costs of renewables and stock-dependent extraction costs of oil.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jeem.2018.03.010

References

Aichele, R., Felbermayr, G., March 2015. Kyoto and carbon leakage: an empirical analysis of the carbon content of bilateral trade. Rev. Econ. Stat. 97, 104–115.
Andrade de Sá, S., Daubanes, J., July 2016. Limit pricing and the (in)effectiveness of the carbon tax. J. Publ. Econ. 139, 28–39.
Benchekroun, H., Halsema, A., Withagen, C., November 2009. On nonrenewable resource oligopolies: the asymmetric case. J. Econ. Dyn. Control 33, 1867–1879.
Benchekroun, H., Halsema, A., Withagen, C., January 2010. When additional resource stocks reduce welfare. J. Environ. Econ. Manag. 59, 109–114.
Benchekroun, H., Van der Meijden, G., Withagen, C., November 2017. OPEC, Shale Oil, and Global Warming - on the Importance of the Order of Extraction. Tinbergen Institute Discussion Papers 16-089/VIII. Tinbergen Institute.
Boden, T., Marland, G., Andres, R., 2015. Global, Regional, and National Fossil-Fuel CO2 Emissions, Technical Report.
Copeland, B.R., Taylor, M.S., March 2005. Free trade and global warming: a trade theory view of the Kyoto protocol. J. Environ. Econ. Manag. 49, 205–234.
Dasgupta, P., Heal, G., 1979. Economic Theory and Exhaustible Resources (Cambridge Economic Handbooks. University Press, Oxford.
Demirer, R., Kutan, A., November 2010. The behavior of crude oil spot and futures prices around OPEC and SPR announcements: an event study perspective. Energy Econ. 32, 1467–1476.
EIA, 2016a. International Energy Statistics. U.S. Energy Information Administration, http://www.eia.gov/beta/international/data/browser.
EIA, 2016b. Short Term Energy Outlook. U.S. Energy Information Administration, https://www.eia.gov/forecasts/steo/report/global_oil.cfm.
EIA, 2016c. U.S. Energy Information Administration, https://www.eia.gov/tools/faqs/faq.cfm?id=33&t=6.
EIA, 2017. International Energy Statistics. U.S. Energy Information Administration, http://www.eia.gov/beta/international/data/browser.
Eichner, T., Pethig, R., August 2011. Carbon leakage, the Green paradox, and perfect future markets. Int. Econ. Rev. 52, 767–805.
EPA, 2015. Inventory of US Greenhouse Gas Emissions and Sinks. U.S. Environmental Protection Agency.
Fischer, C., Salant, S.W., 2014. Alternative climate policies and intertemporal emissions leakage. In: Pittel, K., van der Ploeg, F., Withagen, C. (Eds.), Beyond the Green Paradox. MIT Press, Cambridge, MA, pp. 255–285.
Fischer, C., Salant, S.W., October 2017. Balancing the carbon budget for oil: the distributive effects of alternative policies. Eur. Econ. Rev. 99, 191–215.
Gilbert, R.J., Goldman, S.M., April 1978. Potential competition and the monopoly price of an exhaustible resource. J. Econ. Theory 17, 319–331.
Golosov, M., Hassler, J., Krusell, P., Tsyvinski, A., January 2014. Optimal taxes on fossil fuel in general equilibrium. Econometrica 82, 41–88.
Hamilton, J.D., 2009. Causes and consequences of the oil shock of 2007-08. Brookings Pap. Econ. Activ. 40, 215–283.
Hassler, J., Krusell, P., Olovsson, C., May 2010. Oil monopoly and the climate. Am. Econ. Rev. 100, 460–464.
Heal, G., 1976. The relationship between price and extraction cost for a resource with a backstop technology. Bell J. Econ. 7, 371–378.
Hoel, M., October 1978. Resource extraction, substitute production, and monopoly. J. Econ. Theory 19, 28–37.
Hoel, M., December 1983. Future conditions and present extraction: a useful method in natural resource economics. Resour. Energy 5, 303–311.
Hoel, M., August 1984. Extraction of a resource with a substitute for some of its uses. Can. J. Econ. 17, 593–602.
Hoel, M., December 2011. The supply side of CO2 with country heterogeneity. Scand. J. Econ. 113, 846–865.
IEA, 2016. CO_2 emissions from Fuel Combustion. International Energy Agency, Paris.
IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
Jaakkola, N., May 2015. Strategic Development of Substitutes and Oil Supply, Technical Report.
Kagan, M., van der Ploeg, F., Withagen, C., December 2015. Battle for climate and scarcity rents: beyond the linear-quadratic case. Dyn. Games Appl. 1–30.
Karp, L., Siddiqui, S., Strand, J., September 2016. Dynamic climate policy with both strategic and non-strategic agents: taxes versus quantities. Environ. Resour. Econ. 65, 135–158.
Kaufmann, R.K., January 2011. The role of market fundamentals and speculation in recent price changes for crude oil. Energy Pol. 39, 105–115.
Kesicki, F., March 2010. The third oil price surge - what's different this time? Energy Pol. 38, 1596–1606.
Liski, M., Tahvonen, O., January 2004. Can carbon tax eat OPEC's rents? J. Environ. Econ. Manag. 47, 1–12.
Makris, M., December 2001. Necessary conditions for infinite-horizon discounted two-stage optimal control problems. J. Econ. Dyn. Control. 25, 1935–1950.
Nordhaus, W., 2013. Integrated Economic and Climate Modeling. In: Handbook of Computable General Equilibrium Modeling, vol. 1. Elsevier, pp. 1069–1131. chapter 16.
Nordhaus, W.D., 2017. Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. U. S. A. 114, 1518–1523.
Regnier, E., May 2007. Oil and energy price volatility. Energy Econ. 29, 405–427.
Ryszka, K., Withagen, C., February 2014. Unilateral climate policies: incentives and effects. Environ. Resour. Econ. 1–34.
Salant, S.W., 1976. Exhaustible resources and industrial structure: a Nash-Cournot approach to the world oil market. J. Polit. Econ. 84, 1079–1094.
Salant, S.W., 1979. Staving off the backstop: dynamic limit pricing with a kinked demand curve. In: Pindyck, R. (Ed.), Advances in the Economics of Energy and Resources. JAI Press, Greenwich, Conn.
Seierstad, A., Sydsæter, K., 1987. Optimal Control Theory with Economic Applications. North-Holland, Amsterdam.
Sinn, H.-W., August 2008. Public policies against global warming: a supply side approach. Int. Tax Publ. Finance 15, 360–394.
Sinn, H.-W., 2012. The Green Paradox: a Supply-Side Approach to Global Warming. MIT Press, Cambridge.
SPR, 2016. Inventory. U.S. Strategic Petroleum Reserve, http://www.spr.doe.gov/dir/dir.html.
Stiglitz, J.E., Dasgupta, P., 1981. Market structure and resource extraction under uncertainty. Scand. J. Econ. 83, 318–333.
Stiglitz, J.E., Dasgupta, P., October 1982. Market structure and resource depletion: a contribution to the theory of intertemporal monopolistic competition. J. Econ. Theory 28, 128–164.
Strand, J., September 2013. Strategic climate policy with offsets and incomplete abatement: carbon taxes versus cap-and-trade. J. Environ. Econ. Manag. 66, 202–218.
Strumpf, D., Friedman, N., July 2016. How Much Oil Is in Storage Globally? Take a Guess. [Online; updated 24-July-2016].
Tomiyama, K., November 1985. Two-stage optimal control problems and optimality conditions. J. Econ. Dyn. Control 9, 317–337.
U.S. Department of the Treasury, 2017. Daily Treasury Long Term Rate Data. Department of the Treasury, https://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=longtermrate.
Valente, S., June 2010. Endogenous growth, backstop technology adoption, and optimal jumps. Macroecon. Dyn. 15, 293–325.
Van der Meijden, G., Withagen, C., December 2017. Limit Pricing, Climate Policies and Imperfect Substitution. Tinbergen Institute Discussion Papers 17-104/VIII. Tinbergen Institute.
Van der Meijden, G., Ryszka, K., Withagen, C., 2017. Climate Change: the Role of Arbitrators on the Oil Market, Technical Report.
Van der Ploeg, F., 2012. Breakthrough Renewables and the Green Paradox Technical Report. CESifo Working Paper Series 3986 CESifoGroup Munich.
Van der Ploeg, F., 2016. Second-best carbon taxation in the global economy: the Green Paradox and carbon leakage revisited. J. Environ. Econ. Manag. 78, 85–105.